Current Trends and Challenges in Satellite Laser Ranging

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Abstract Satellite Laser Ranging (SLR) is used to measure accurately the distance from ground stations to retro-reflectors on satellites and on the Moon. SLR is one of the fundamental space-geodetic techniques that define the International Terrestrial Reference Frame (ITRF), which is the basis upon which many aspects of global change over space, time, and evolving technology are measured; with VLBI the two techniques define the scale of the ITRF; alone the SLR technique defines its origin (geocenter). The importance of the reference frame has recently been recognized at the inter-governmental level through the United Nations, which adopted in February 2015 the Resolution Global Geodetic Reference Frame for Sustainable Development. Laser Ranging provides precision orbit determination and instrument calibration and validation for satellite-borne altimeters for the better understanding of sea level change, ocean dynamics, ice mass-balance, and terrestrial topography. It is also a tool to study the dynamics of the Moon and fundamental constants and theories. With the exception of the currently in-orbit GPS constellation, all GNSS satellites now carry retro-reflectors for improved orbit determination, harmonization of reference frames, and in-orbit co-location and system performance validation; the next generation of GPS satellites due for launch from 2019 onwards will also carry retro-reflectors. The ILRS delivers weekly realizations that are accumulated sequentially to extend the ITRF and the Earth Orientation Parameter series with a daily resolution. SLR technology continues to evolve towards the next-generation laser ranging systems and it is expected to successfully meet the challenges of the GGOS2020 program for a future Global Space Geodetic Network. Ranging precision is improving as higher repetition rate, narrower pulse lasers, and faster detectors are implemented within the network. Automation and pass interleaving at some stations is expanding temporal coverage and greatly enhancing efficiency. Discussions are ongoing with some missions that will allow the SLR network stations to provide crucial, but energy-safe, range measurements to optically vulnerable satellites. New retro-reflector designs are improving the signal link and enable daylight ranging that is now the norm for many stations. We discuss many of these laser ranging activities and some of the tough challenges that the SLR network currently faces.

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1 Introduction

In this paper, we review the technique of Satellite Laser Ranging (SLR), which is coordinated by the International Laser Ranging Service (ILRS) (Pearlman et al., 2002). We discuss emerging new technology, the ongoing expanding constellations of satellites that require the high-quality tracking that is afforded by laser ranging, and a number of new or proposed new sites that are under development, often in conjunction with

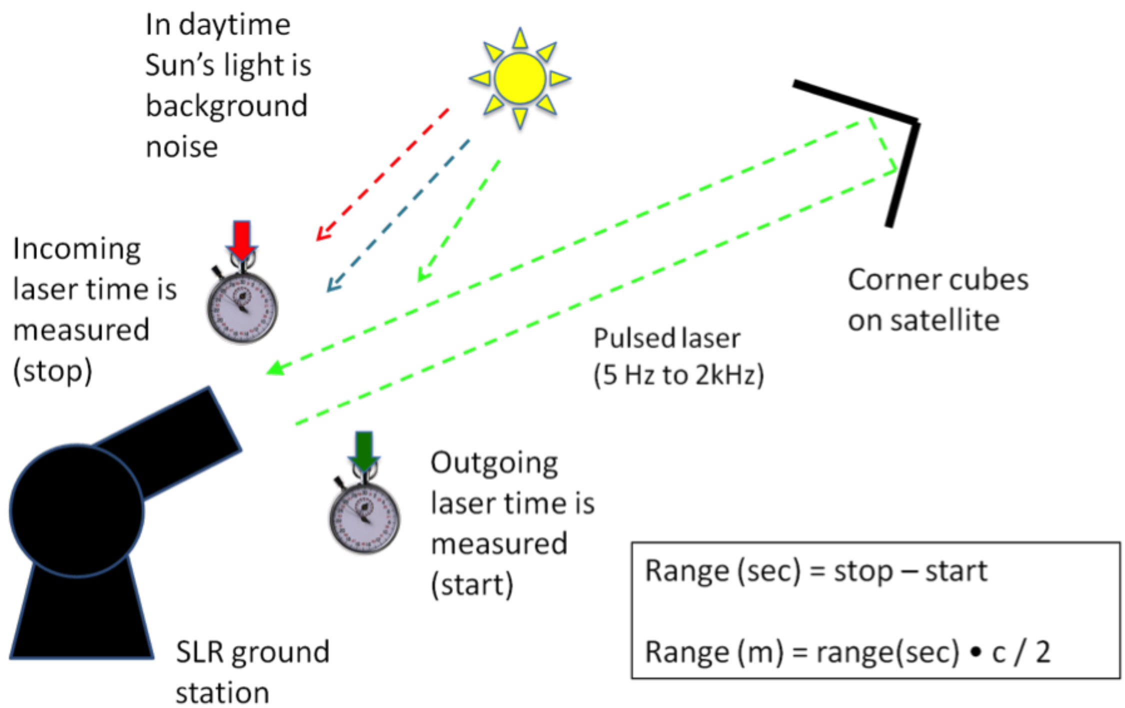

Fig. 1 The technique of satellite laser ranging.

VLBI, GNSS, and DORIS. The ILRS community is also addressing and embracing novel applications for its technique, including satellite attitude determination and debris tracking. The ILRS continues to have a major role within the emerging Global Geodetic Observing System (GGOS) (Plag and Pearlman, 2009), both in support of precise orbit determination for applications satellites and in its crucial role in defining the origin and scale of the terrestrial reference frame. For this work, high-quality, multi-technique sites are essential: the space-observational services—the IDS, IGS, ILRS, and IVS—together supply the data and products to meet the GGOS Mission, which includes as a major challenge the determination of the reference frame with a precision of 1 mm and a stability of 0.1 mm yr^{-1}, which must be realized via inter-technique site ties and combination of analysis products (site position, velocity, Earth orientation). We conclude with a discussion of some recent work carried out at the SGF ILRS Analysis Center on the detection of systematic effects in laser ranging observations and analyses and their impact on ITRF scale.

2 The Technique of Satellite Laser Ranging

Satellite Laser Ranging, shown schematically in Figure 1, directly measures the range between a ground station and a satellite using very short laser pulses, corrected for refraction, satellite center of mass, and the internal delay of the ranging machine.

The state-of-the-art is millimeter precision for averaged measurements (normal points) with centimeter-level accuracies. The most able stations can track satellites at distances from 300 km to more than 22,000 km by day and at night. Each station tracks independently, but overall satellite priorities are set by the ILRS and can be used to encourage the stations to concentrate on new launches, for example. A network of stations can also in principle work together via real-time status exchange to optimize tracking. The key to the technique's success is that it requires only a passive retroreflector of sufficient optical cross section to be placed on the satellite. The observations, both normal points and full-rate, are made available to the worldwide community in near real-time through the NASA-supported

Crustal Dynamics Data Information System (CDDIS http://cddis.nasa.gov) and the European Data Centre (EDC http://edc.dgfi.tum.de).

3 SLR Science and Applications

The precise laser range measurements to retro-reflector-carrying satellites lead, in some cases in conjunction with other tracking techniques such as GNSS and DORIS, to precise orbit determination for those satellites and also to a time history of station positions and motions. Arguably the most important product of satellite laser ranging is its critical contribution to the realization of the Terrestrial Reference Frame, upon which a huge number of research projects and societal enterprises depend, from monitoring global sea-level changes, GIA, ice sheet mass-balance, to satellite navigation and surveying for example. The SLR contribution to a series of realizations, including the most recent ITRF2014 (Altamimi et al., 2016), is in the determination of the origin of the frame at the mass center of the Earth system and, together with VLBI, its scale. The primary satellites used for reference frame determination are the two LAGEOS satellites, orbiting at nearly 6,000 km above the Earth; LAGEOS is shown in Figure 2. Future plans to improve the precision and accuracy of the ITRF include the use of range measurements to the ASI LAser RElativity Satellite (LARES), launched by ESA in 2012 into a circular orbit 1400 km above the Earth.

Fig. 2 The LAGEOS geodetic satellite (courtesy of NASA).

Since the 1970s the laser ranging network has supported more than 150 space missions, including the earliest altimeter missions Geos-3 and Seasat. Several missions have been ‘rescued’ by laser ranging when other tracking systems have failed; for instance, on the ESA mission ERS-1, the experimental PRARE tracking system failed soon after launch in 1991, and SLR provided the only tracking data for precise orbit determination (POD) and for calibration/validation of the altimeter data. With multi-technique tracking of altimeter missions such as the JASON series, a critical role for laser ranging is independent validation of orbital accuracy and resolution of phase center offsets for on-board GNSS antennae. This role for SLR, which also involves its use in routine POD, will continue into the future; the most recent addition to the ESA Copernicus Programme is the Sentinel-3 two-satellite series, with Sentinel-3A launched in April 2016. These satellites carry radar altimeters, two GPS receivers, a DORIS system, and a laser retro-array, measurements from all of which will be used by such agencies as CNES for POD (Fernández et al., 2015).

4 Recent Tracking Station Initiatives

There has been a recent expansion of the Russian SLR network, for instance, the new system in Brazil and one expected at Hartebeesthoek, primarily to support GLONASS tracking for improved orbital accuracy and for time transfer and to join international efforts to improve the reference frame as per the GGOS initiative. The NASA Space Geodesy Project has ambitious plans to upgrade existing facilities and deploy new instrumentation to create new GGOS core sites, for example at McDonald, Texas and on Hawaii, and other agencies are getting involved in these global efforts to realize the GGOS concepts. These agencies include the Norwegian Mapping Agency with a planned multi-technique site at Ny Ålesund to deploy a NASA SLR system in a few years’ time and the South Korean Astronomy and Space Science Institute that is developing a site at Sejong to include an existing modern kHz-class SLR system. The existing and projected ILRS network of stations is shown in Figure 3.

A growing number of ILRS stations now operate at kHz laser repetition rates. The advantages of operating at these rates compared to the legacy systems that work at rates of 5–10 Hz include much more rapid acquisition of the target, enabling pass-interleaving and thus

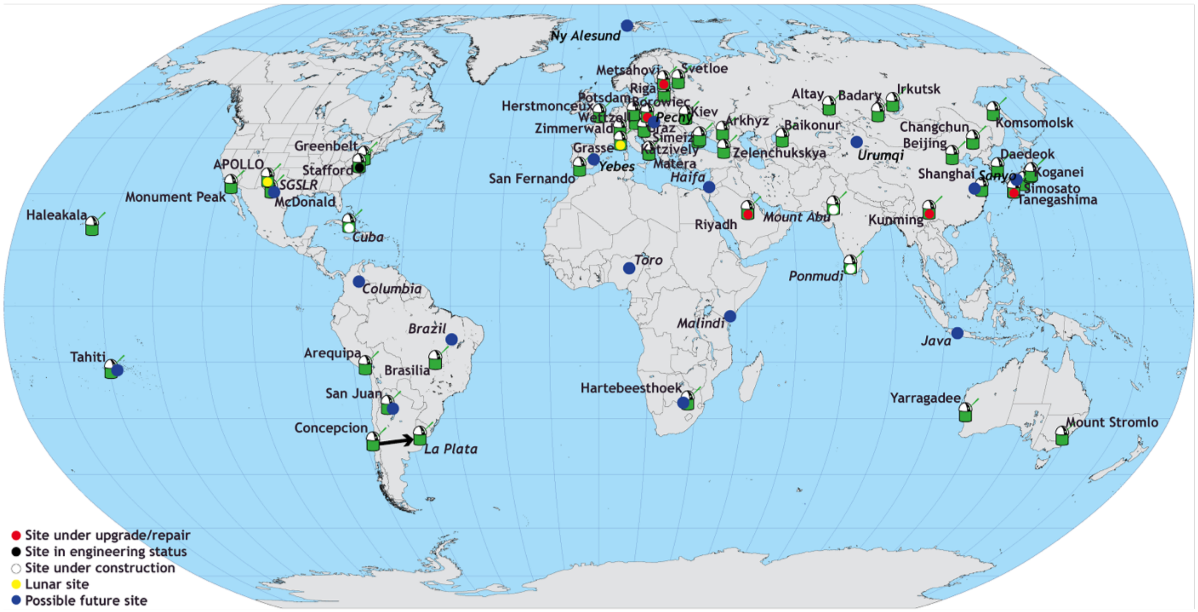

Fig. 3 Projected ILRS Network (ILRS CB).

increased coverage, and the ability to reach sub-mm normal-point precision very quickly. The kHz lasers also tend to have very short pulse lengths and low energy per pulse (at 1-mJ level), so an added benefit is high-resolution interrogation of the distribution of corner cubes within the array. An example of this impressive capability is shown in Figure 4, where tracks from individual corner-cubes are clearly visible. The

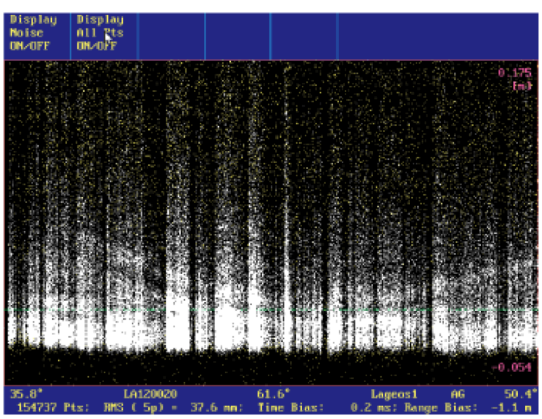

Fig. 4 kHz ranging to LAGEOS from Graz (courtesy G. Kirchner).

availability of this high-resolution, high repetition-rate range data has led to new work to monitor the time-variation of the spin vectors of many of the geodetic satellites. For instance, recent work by Kucharski and others (Kucharski et al., 2014a) has resulted in a ten-year time series of the direction in inertial space of the spin axes of the two Etalon satellites; the series shows that both axes behave in the same manner, with the direction in declination being very stable and constant throughout. This sort of information has great potential for accurate models of non-gravitational forces on these important classes of geodetic satellites.

5 Space Debris

A growing concern is the lack of accurate orbital information for the huge number of inactive pieces of space junk in orbit around the Earth. Debris includes rocket bodies, heat shields, and other parts of satellites, as well as formerly active satellites. Several, mainly European, stations have carried out some ranging experiments, both to once-active satellites fitted with retro-reflectors as well as to non-cooperative, inert satellites. A good example of the results that can be achieved by such monitoring of currently-inactive satellites is that published by Kucharski et al. (Kucharski et al., 2014b) from laser range observations of the Envisat satellite that suddenly failed on 8 April 2012. On that date, all communication was lost, a few weeks after the satellite had achieved ten productive years in orbit. Laser ranging was resumed in 2013, and Kurcharski's analysis showed that Envisat is rotating in a counter-clockwise direction with an inertial period in September 2013 of 135 s. Many stations continue to track Envisat, as well as TOPEX/Poseidon, in order to advance these attitude studies. A recent O-C range plot obtained at the Herstmonceux SLR station from a pass of TOPEX/Poseidon is shown in Figure 5; a clear, steady rotational signature is seen in the track of laser returns.

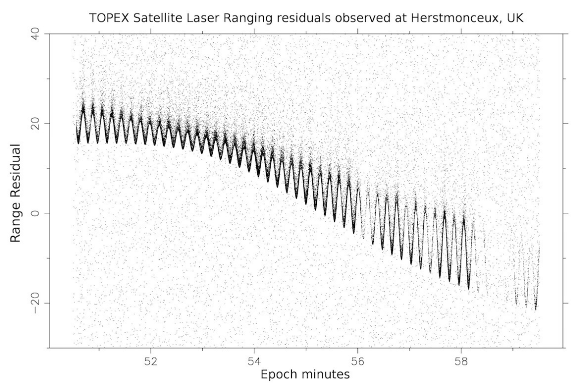

Fig. 5 kHz ranging to defunct satellite TOPEX/Poseidon from Herstmonceux.

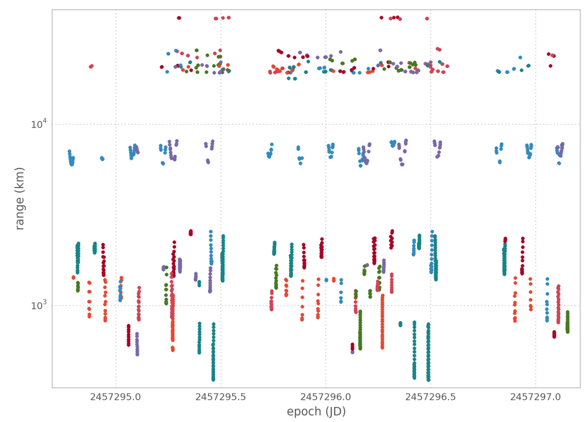

Fig. 6 Example of laser range normal points obtained at Herstmonceux as a funtion of satellite altitude.

6 Increasing Numbers of Satellites

Particularly demanding are the expanding constellations of GNSS satellites, all of which are fitted with laser retro-reflectors: GLONASS (Russia), Galileo (Europe), Beidou (Compass: China), IRNSS (India), and QZSS (Japan). An example of what this demand means for the stations is shown in Figure 6 covering a two-day period, where each point represents a laser range normal point obtained at Herstmonceux from a satellite at the given height above the Earth. Many range measurements are obtained from the GNSS satellites, at heights of approximately 20,000 km, as well as one at geosynchronous distance (IRNSS). The GNSS mission operators request from the ILRS as much laser tracking as possible, in order to support investigations into co-location of techniques in space, to strengthen precise clock and orbit determination, and to strengthen links between reference frames. The research community is taking advantage of the greater numbers of laser range measurements to the GNSS satellites to investigate many of these issues; for example, see Sośnica et al. (2015). To test each station's capabilities in tracking GNSS, the ILRS Central Bureau has run a series of three campaigns. Most of the strongest stations took part, as shown in the global map of Figure 7. The stations were asked to track at high priority just six of the possible 24 GLONASS satellites, Compass-M3, and four of the Galileo constellation. The results were that reasonably high data yields can be expected when sky conditions are very good, but that there is a strong need for more data in daylight. Daytime ranging to these high satellites is very challenging for most stations. This point is demonstrated clearly in Figure 8, which gives total numbers of GNSS normal points obtained by the Network during the third campaign (August to October 2015) binned according to local time. It is clear that the numbers of daytime observations are about one third of those during nighttime. Also shown for comparison is an equivalent non-campaign period during 2014, where the total yield is lower by one third and the daytime tracking is disproportionally even lower.

One concern expressed when the ILRS was asked for increasing priority to be given to tracking GNSS was that tracking of the primary geodetic LAGEOS

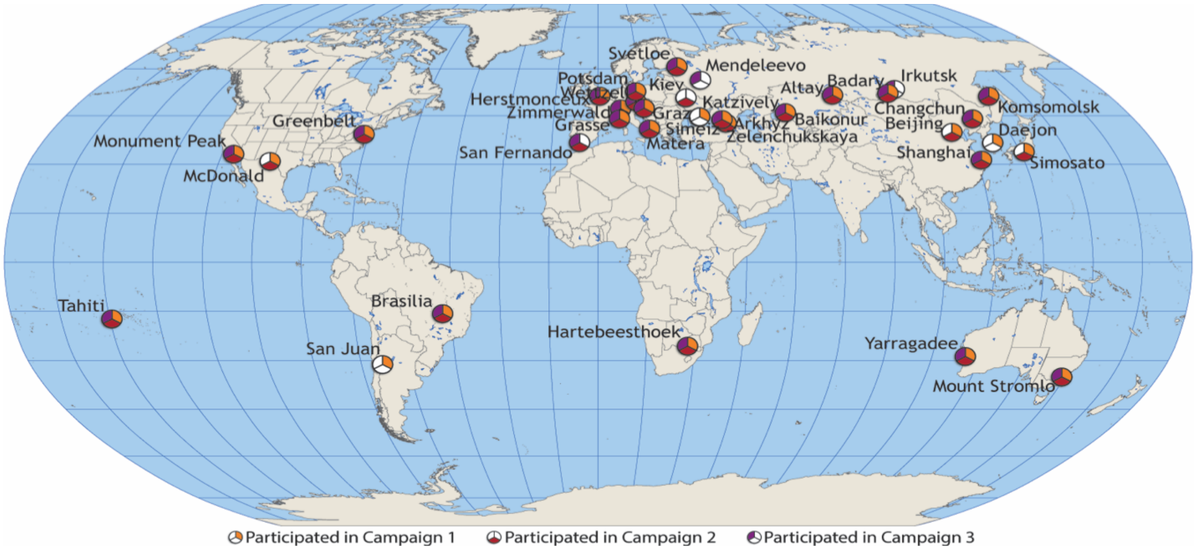

Fig. 7 ILRS stations that contributed to the three GNSS tracking campaigns of 2015.

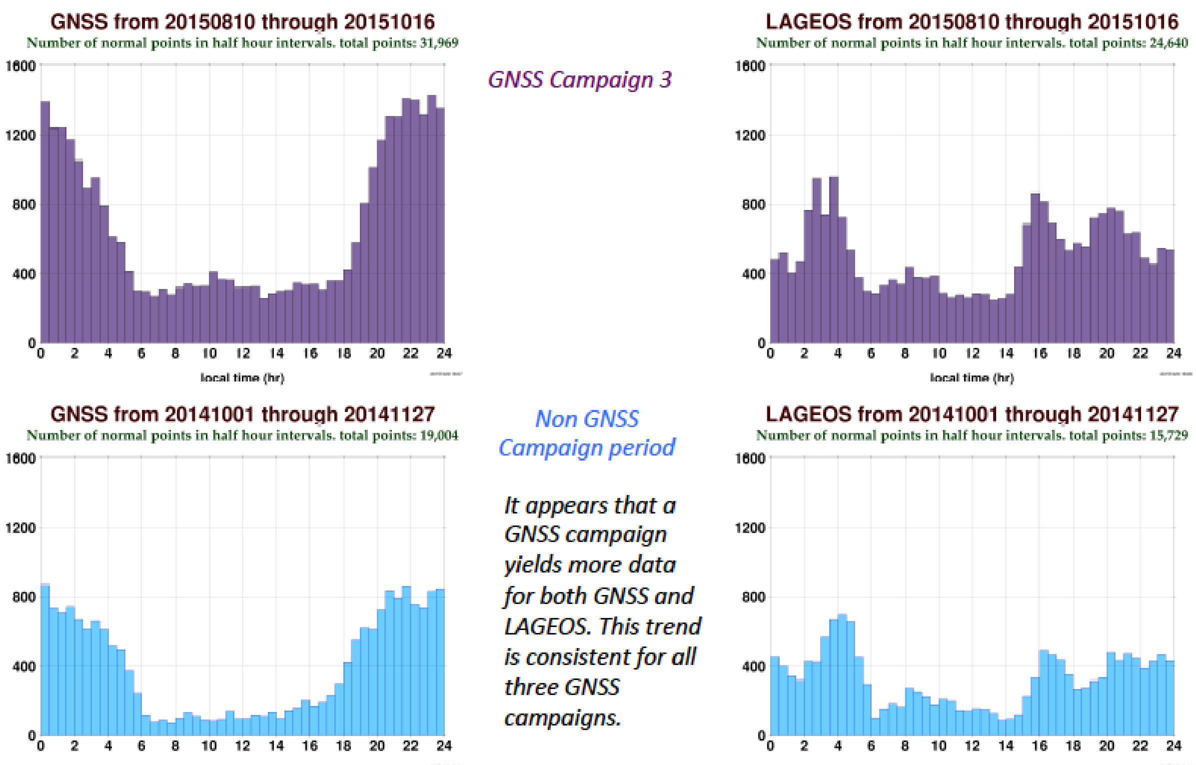

Fig. 8 ILRS Network yield from GNSS tracking: both during and outside Campaign number 3.

satellites would suffer. Interestingly, however, the reverse effect has proven to be true, as also illustrated in Figure 8: during the third GNSS campaign, increased numbers of normal points were obtained on the two LAGEOS satellites, both by day and night. This very encouraging trend is consistent for all three GNSS campaigns.

7 Terrestrial Reference Frame

Of course, the primary application of SLR is in the realization of the International Terrestrial Reference Frame (ITRF), e.g., ITRF2014 (Altamimi et al., 2016). The need for a consistent global reference frame to support a huge number of societal needs from global sea-level monitoring and disaster management to bridge-building was recognized at the UN level in 2015: the Resolution A Global Geodetic Reference Frame for Sustainable Development, (GGRF) (United Nations General Assembly, 2015) was passed by 52 Member States. The geodetic Services' contributions to the realization of the ITRF are:

- **SLR:** Uniquely provides Earth center of mass, the origin of the ITRF;
- **VLBI:** Provides EOP parameters and the connection with the Celestial Reference Frame;
- **SLR** and **VLBI:** Independently provide Scale;
- **GNSS:** Global coverage and density;
- **DORIS:** Global coverage.

Figure 9 shows the numbers of passes of the two LAGEOS satellites tracked by the ILRS stations during the past year. The high-performing stations include Zimmerwald, Changchun, Monument Peak, Hartebeesthoek, and, of course, the most prolific station in the Network, Yarragadee, Western Australia.

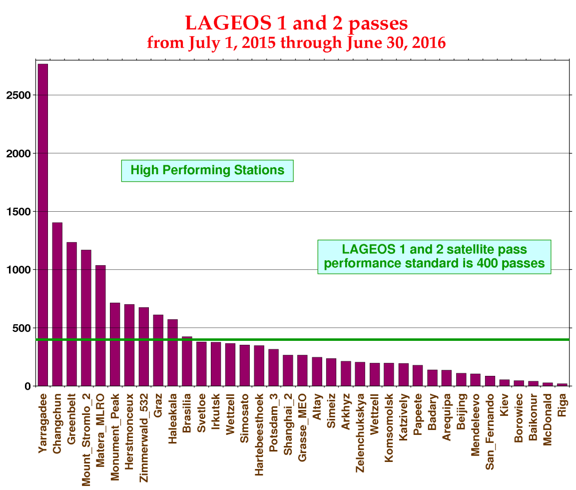

Fig. 9 Tracking of the LAGEOS satellites during the past year (ILRS CB).

7.1 ITRF Scale

Of particular interest in recent realizations of the terrestrial reference frame, ITRF2008 (Altamimi et al., 2011) and ITRF2014 (Altamimi et al., 2016), is the persistent systematic difference in scale as determined from the two techniques of SLR and VLBI, which alone are capable of high-precision scale determination. The difference in scale for ITRF2014 is 1.37 ± 0.01 ppb (Altamimi et al., 2016), more than 8 mm at the equator, and in the sense that the scale determined by the SLR technique is smaller than that from VLBI. This persistent difference in scales is intriguing and points to systematic problems in either or both techniques as well as to potential site-tie problems. To ascertain the extent to which possible systematic effects in laser ranging to the LAGEOS satellites may be responsible for at least some of the scale discrepancy with the VLBI result, the UK ILRS Analysis Center at the Space Geodesy Facility, Herstmonceux (SGF AC) carried out an investigation using fifteen years of LAGEOS and LAGEOS-2 observations. The standard ILRS reference-frame determination procedure, as agreed by the ILRS Analysis Standing Committee (Pavlis and Luceri, 2013), is to treat a number of ranging stations as error-free in the weekly orbital solutions, along with other stations for which a systematic range error (range bias, RB) may be solved for simultaneously with station geocentric coordinates and Earth orientation parameters. This was the procedure used in the production of the ILRS contribution to the realization of ITRF2008 and ITRF2014. The thesis of the SGF AC work is that, if indeed some systematic range error is present in any of the stations that are assumed error-free, then that systematic error will have been absorbed during the least-squares estimation process primarily in station height and thus enter in corrupted form the ITRF. On-going daily and weekly quality checks regularly carried out at several ILRS Analysis Centers (http://ilrs.gsfc.nasa.gov/science/analysisCenters/) that use coordinates taken from, for example, ITRF2008, will thus not detect the hidden range error. Causes of small systematic range errors may be non-linearity in the time-of-flight counters (Appleby et al., 2008), error in the survey distance of the calibration board, and inappropriate center-of-mass corrections applied to the range measurements to refer them to the centers of

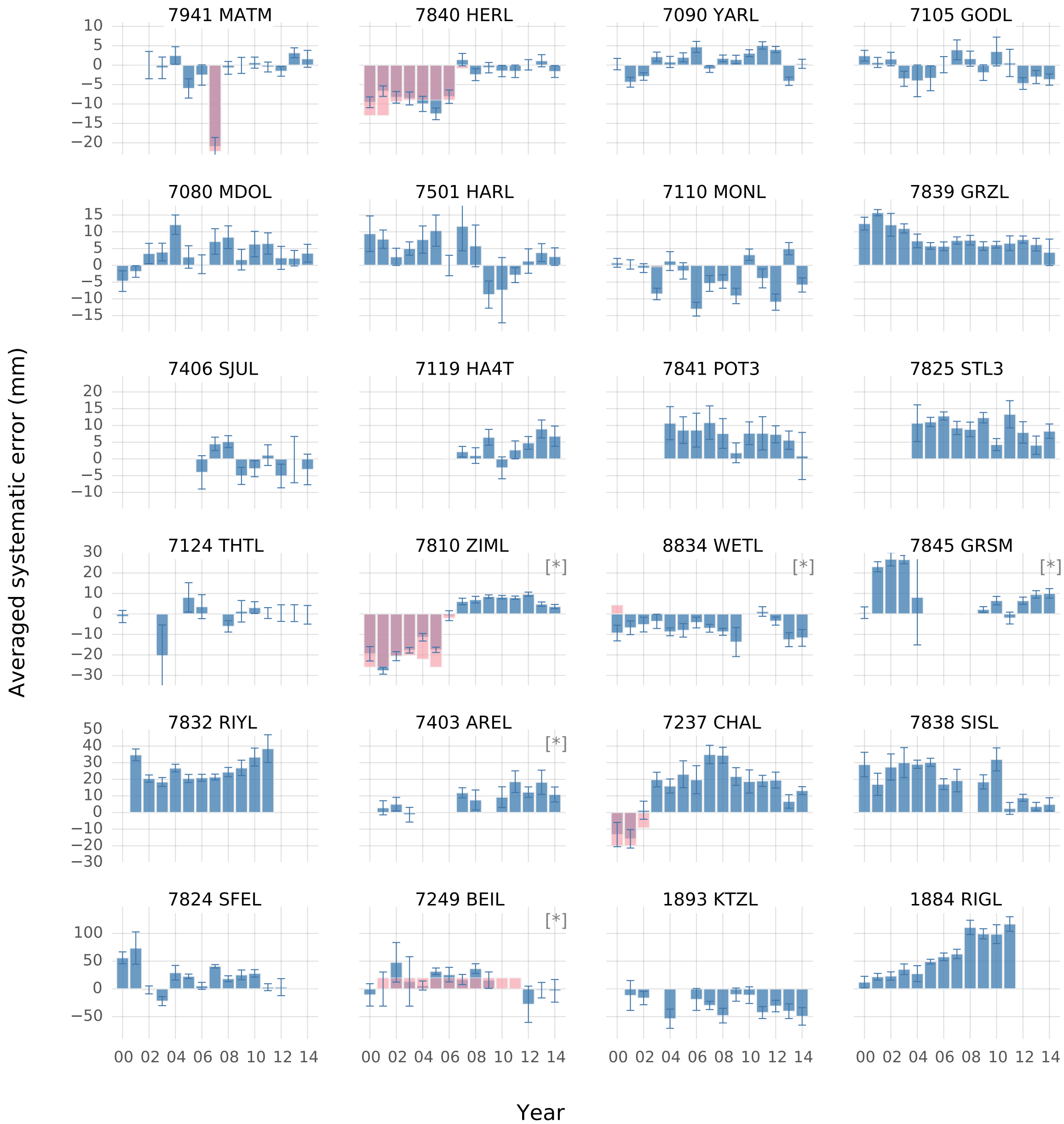

Fig. 10 Yearly-averaged station range bias determined simultaneously with reference frame in weekly solutions: shaded values correspond to previously-known systematics.

the LAGEOS satellites (Otsubo and Appleby, 2003). The SGF AC approach was, for the period 2000 to 2014, to compute weekly solutions for LAGEOS and LAGEOS-2 state vectors, station coordinates, daily Earth orientation parameters, and a single range bias value for each of the contributing stations, using SGF's in-house SATAN analysis package. No *a priori* range bias values were applied to any of the observations. The solutions for stations' range bias, averaged yearly from the weekly solutions, are shown in Figure 10. It is clear that most stations have some level of systematic bias, with some being consistent throughout the time period. There is evidence at some stations of dramatic improvement, such as the change from large (12 mm) negative bias at Herstmonceux to very small values from 2007 onwards. This problem was caused by the difficulty in application of known non-linearity in time-of-flight counters in use at the station until replacement by a high-accuracy event timer in February 2007 (Appleby et al., 2008). A similar dramatic improvement is evident at Hartebeesthoek from 2011 onwards. An example of a consistent range bias is that at Graz, where a positive bias of at least 5 mm is present throughout despite an upgrade to kHz ranging in 2002. The final step in this analysis is to carry out 7-parameter Helmert solutions (three translations, three rotations, and one scale difference) between the all-station weekly RB solutions and standard ILRS solutions where RB is solved only for a subset of the stations; to re-iterate, this latter scheme was used by all ACs for the ILRS contribution to ITRF2014. From the time series of scale differences, the final solution for mean scale is found to be $+0.7 \pm 0.1$ ppb, approximately half the difference in scale between the SLR and VLBI solutions in ITRF2014 (Altamimi et al., 2016). A full account of this work is given in a recent publication (Appleby et al., 2016).

8 Conclusions

The ILRS Satellite Laser Ranging technique is in a situation of continuing growth and improvement. New applications are emerging, and the list of new missions that require laser support for precise orbit determination is ever increasing. New stations are being built, and it is particularly encouraging to see new and planned sites at geographically important locations, such as at high latitudes. Care must continue to be taken that the primary geodetic application of SLR, that of realization of the origin and scale of the ITRF, be addressed at the highest level of accuracy and by prolific observations of the LAGEOS satellites by the core ILRS SLR stations, including the long-running excellent system nearby at Hartebeesthoek.

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